AGU100 ADVANCING EARTH AND SPACE SCIENCE

Earth's Future

RESEARCH ARTICLE
10.1029/2018EF000939

Key Points:
- The total estimated groundwater depletion in India is in the range of 122 to 199 billion m^3
- The CO_2 emissions due to bicarbonate is ~0.72 million tons/year
- The environmental problem of groundwater depletion in India is much more serious than the associated CO_2 emissions

Supporting Information:
- Supporting Information S1

Correspondence to:
V. Mishra,
vmishra@iitgn.ac.in

Citation:
Mishra, V., Asoka, A., Vatta, K., & Lall, U. (2018). Groundwater depletion and associated CO_2 emissions in India. *Earth's Future*, *6*, 1672–1681. https://doi.org/10.1029/2018EF000939

Received 24 MAY 2018
Accepted 18 OCT 2018
Accepted article online 25 OCT 2018
Published online 17 DEC 2018

©2018. The Authors.
This is an open access article under the terms of the Creative Commons Attribution-NonCommercial-NoDerivs License, which permits use and distribution in any medium, provided the original work is properly cited, the use is non-commercial and no modifications or adaptations are made.

Groundwater Depletion and Associated CO_2 Emissions in India

Vimal Mishra[1], Akarsh Asoka[1], Kamal Vatta[2], and Upmanu Lall[3]

[1]Civil Engineering and Earth Sciences, Indian Institute of Technology Gandhinagar, Ahmedabad, India, [2]Columbia International Project Trust (CIPT), New Delhi, India, [3]Columbia Water Center, Columbia University, New York, NY, USA

Abstract India, the world's largest groundwater user, withdraws about 230-billion-m^3 groundwater annually for irrigation. Excessive groundwater pumping in India leads to rapid groundwater depletion and CO_2 emissions. Here using multiple data sources (observation wells and Gravity Recovery Climate Experiment) to estimate groundwater depletion in India, as well as the associated chemistry and the pumping energy requirements, we provide the first estimate of the potential CO_2 emissions due to bicarbonate extraction (CO_2 release due to lowering of groundwater table) and groundwater pumping. We show that combined annual CO_2 release due to bicarbonate extraction and pumping in India is approximately 32.01–131.74 million tons (31.29–131.02 million tons for pumping and 0.72 million tons for bicarbonate). The total estimated groundwater depletion in India is in the range of 122 to 199 billion m^3 from the observation wells (1996–2016) and Gravity Recovery Climate Experiment (2002–2016). The CO_2 emissions due to bicarbonate (~0.72 million tons/year) are dominated by those due to groundwater pumping (31.29–131.02 million tons/year) in India. However, the total (pumping and bicarbonate) estimated annual CO_2 emission from groundwater is less than 2–7% of the total (annual) CO_2 emission from India. Based on our unique data set collected from more than 500 farmers in Punjab, we show that a low-cost intervention for irrigation scheduling based on soil moisture information can provide a sustainable solution by reducing groundwater pumping and CO_2 emissions. The environmental problem of groundwater depletion in India is much more serious than the associated CO_2 emissions, and hence, there is an urgent need for a regulation of groundwater use.

Plain Language Summary Groundwater depletion in India remains one of the most critical issues related to future food and freshwater security. Groundwater depletion causes a significant emission of CO_2 in the United States as shown in the previous study. Since India is the largest consumer of groundwater, we hypothesized that CO_2 emission due to groundwater depletion in India would be considerable. We, however, find that CO_2 emission in India due to groundwater depletion and pumping is only about 2% of the total emissions combined from all the sectors. Our results show a significant decline (200 billion m^3) in groundwater in India, especially in the northwestern and northcentral regions. We show that curbing the depletion of groundwater in India is a major challenge rather than reducing CO_2 emission due to groundwater depletion and pumping.

1. Introduction

Groundwater is a lifeline for food and water security for millions of people in India (Kulkarni et al., 2015), the largest consumer of groundwater in the world (Aeschbach-Hertig & Gleeson, 2012; Shah, 2009). About 88% of the total groundwater withdrawal in India is used for irrigation (IDFC Foundation 2013). Groundwater pumping for irrigation (Rodell et al., 2009; Tiwari et al., 2009) combined with the weakening of the Indian summer monsoon (Asoka et al., 2017) has resulted in widespread groundwater depletion in India in the last 20 years. The rate of abstraction in many regions is higher than groundwater recharge (Siebert et al., 2010), causing a recurrent water stress (Hanasaki et al., 2008), persistent groundwater depletion (Gleeson et al., 2010), and long-lasting impacts on streamflow, lakes, and wetlands (Wada et al., 2010). The Indo-Gangetic plain and northwest India have experienced a severe decline in groundwater storage (Asoka et al., 2017; Rodell et al., 2009; Tiwari et al., 2009) and corresponds to one of the largest groundwater footprints in the world (Gleeson et al., 2012).

After the green revolution in the 1970s, the net irrigated area in India expanded from 31 to 60 million ha between 1970 and 2007, out of which nearly 80% was contributed by groundwater (Shankar et al., 2011). About 60% of irrigation in India was sourced from groundwater during 2000–2007 (Shankar et al., 2011).

10.1029/2018EF000939

The expansion of groundwater-based irrigation in India is due in part to the central government procuring wheat and rice from arid regions and the governments in those states providing highly subsidized electricity for agricultural pumping systems. The result is a rapid depletion in groundwater in India (Shah et al., 2012). While the impacts of unsustainable groundwater consumption on food and freshwater security are well documented (Shah, 2009; Shankar et al., 2011), the role of groundwater depletion in India on CO_2 emissions due to bicarbonate and pumping remains unrecognized. Moreover, approaches to managing groundwater sustainably in India are not well established (R. M. Fishman et al., 2011). Here using the observational and satellite-based data sets, we first identify the spatiotemporal extent of groundwater depletion during 1996–2016. We use a well-distributed record of groundwater-related measures (e.g., specific yield, bicarbonate concentration, and electric pumps) to estimate CO_2 emissions due to bicarbonate and pumping in India. Using a unique field survey data set, we show that water savings in irrigation can be a prominent driver of sustainable management of groundwater in India.

2. Materials and Methods

We collected groundwater well data from Central Ground Water Board (CGWB), which monitors groundwater table four times in a year (January, May, August, and November) at more than 24,000 locations. Groundwater well observations were obtained from 1996 to 2016 from the India-Water Resources Information System. The below-ground-level well observations are available for January, May, August, and November. We apply Grubbs test (Grubbs, 1969) to detect outliers in monthly groundwater level observations. After removing outliers, we selected 5,875 well observations that are having at least 16 years of observation out of total 21 years.

Additionally, we obtained terrestrial water storage (TWS) from the Gravity Recovery Climate Experiment (GRACE). Groundwater anomalies (GWAs) at 1° resolution were derived after removing surface water storage (sum of surface water, soil moisture, and canopy storage) from GRACE TWS anomaly for 2002–2016. Monthly TWS anomaly was obtained from the Centre for Space Research at the University of Texas, Austin; NASA's Jet Propulsion Laboratory; and from Deutsches GeoForschungs Zentrum. We applied a 300-km Gaussian filter to reduce the random errors in the data while scaling factors were applied to minimize the attenuation caused due to sampling and postprocessing. To estimate surface water storage (canopy water + soil moisture + snow water equivalent), we used monthly surface water storage data from the four land surface models (VIC, Noah, CLM, and MOSAIC) that are part of the Global Land Data Assimilation System. The ensemble of GWAs was estimated using the three products from GRACE (Jet Propulsion Laboratory, Centre for Space Research, and Deutsches GeoForschungs Zentrum) and four (VIC, Noah, CLM, and MOSAIC) Global Land Data Assimilation System products.

We obtained the bicarbonate ions (HCO_3^-) concentration data in milligrams per liter from CGWB groundwater year book of states for 2013–2015 (http://cgwb.gov.in/GW-Year-Book-State.html). The CGWB monitors groundwater quality in the pre-monsoon season when the concentrations of the ions are maximum. We aggregated the HCO_3^- ion concentration to mean district level observations. Downward percolated and infiltrated water is enriched in CO_2, which can act as a weathering agent. Several factors like frequency of rainfall can influence the chemical composition of groundwater. Before reaching the saturated zone, water is charged with oxygen and carbon dioxide and slowly CO_2 associated with water gets released (equation (1)):

$$CO_2 + H_2O \leftrightarrow H_2CO_3 \leftrightarrow H^+ + HCO_3^-. \tag{1}$$

As most of the aquifers contain sand, gravel, clay, and calcite ($CaCO_3$), the H^+ ion reacts with calcite and creates bicarbonate and calcium (Wood & Hyndman, 2017; Ca^{2+}).

$$H^+ + CaCO_3 \rightarrow HCO_3^- + Ca^{2+} \tag{2}$$

When groundwater is exposed to the atmosphere, CO_2 will be released to atmosphere while calcite is precipitated. The atmospheric contribution due to groundwater depletion can be estimated as described in Wood and Hyndman (2017):

Atmospheric CO_2 contribution = depletion in groundwater X equivalent concentration of CO_2 in groundwater.

The detailed methodology of CO_2 release due to groundwater depletion can be found in Wood and Hyndman (2017). To estimate CO_2 release from groundwater depletion, we used district-level bicarbonate data, groundwater well data, and specific yield data. Specific yield (%) for major aquifers in India was obtained from CGWB (Asoka et al., 2017). Using groundwater table data, we first estimated the trend in GWAs for each well located within a district boundary. We performed trend analysis using a nonparametric Mann-Kendall (Mann, 1945) and Sen's slope method (Sen, 1968). After estimating the change in groundwater level between 1996 and 2016 for each well, we estimated the median change in groundwater level for each district using all the observational wells within a district. Then, the median change in groundwater level was multiplied by average specific yield for each district to obtain an effective change in groundwater. Finally, we multiplied the area of each district with the groundwater change to estimate the change in groundwater volume. Since our aim was to provide a conservative estimate of CO_2 emission due to groundwater depletion in India, we mainly focused on the regions where groundwater has depleted. Therefore, we selected only the districts that experienced groundwater depletion for the analysis.

We used mean bicarbonate concentration for each district, which was converted into equivalent CO_2 concentration by using the following equation:

$$Ca(HCO_3)_2 \rightarrow CO_2 + H_2O + CaCO_3 \tag{3}$$

The above equation can be finally simplified as:

$$\text{Equivalent } CO_2 \text{ concentration} = \left(HCO_3^- \ (\text{mg/L})\right) \times 44)/61.$$

As mentioned in Wood and Hyndman (2017), we assumed that only half of the bicarbonate is converted to CO_2 after reentry of the groundwater to the surface. Using the depleted volume of groundwater and mean bicarbonate concentration, the total amount of CO_2 released to the atmosphere was estimated. Our method provides a distributed assessment of CO_2 release to the atmosphere, as we use bicarbonate values for each district, while Wood and Hyndman (2017) estimated the total release of CO_2 based on a single estimate of 190 mg/L for the entire United States.

To check the robustness of our results estimated using the groundwater well observations, we used the GWA data from the GRACE. For each 1° grid, we estimated the volume of groundwater depletion after estimating changes in GWAs. For each grid, area-weighted bicarbonate concentration was determined using the district level CGWB data. Similar to groundwater well data, we calculated CO_2 emission due to groundwater depletion utilizing the GRACE data sets.

Apart from CO2 emission due to bicarbonate extraction, we also estimated emission due to pumping of groundwater considering the volume of water pumped and the groundwater depth. The distribution on pumps, which are predominantly used for irrigation, for each state at different depths was obtained from the census of minor irrigation. Finally, energy required for groundwater pumping can be calculated as

$$\text{Energy(kWh)} = \frac{9.8 \times \text{lift(m)} \times \text{mass(kg)}}{3.6 \times 10^6 \times \rho.},$$

where ρ is pumping efficiency; CO_2 emission to lift 1,000 m^3 water to 1-m lift with pumping efficiency of 30% can be estimated by multiplying an emission factor ($kgCO_{2e}$/kWh).

3. Results

3.1. Estimates of Groundwater Depletion

We begin our analysis by highlighting the factors that contribute to groundwater depletion in India (Figure 1). A large part of India has more than 60% of the total area irrigated with groundwater resources (Figure 1a). Areas that receive intensive groundwater-based irrigation are located in the Indo-Gangetic Plain, northwestern, central, and western parts of India (Figure 1). More remarkably, a few regions (western India and Indo-Gangetic Plain) have more than 90% of their area irrigated with groundwater resources. The net irrigated area from different sources, mainly tube wells, has increased (except for tanks) between 1950 and 2010 (Figure 1b).

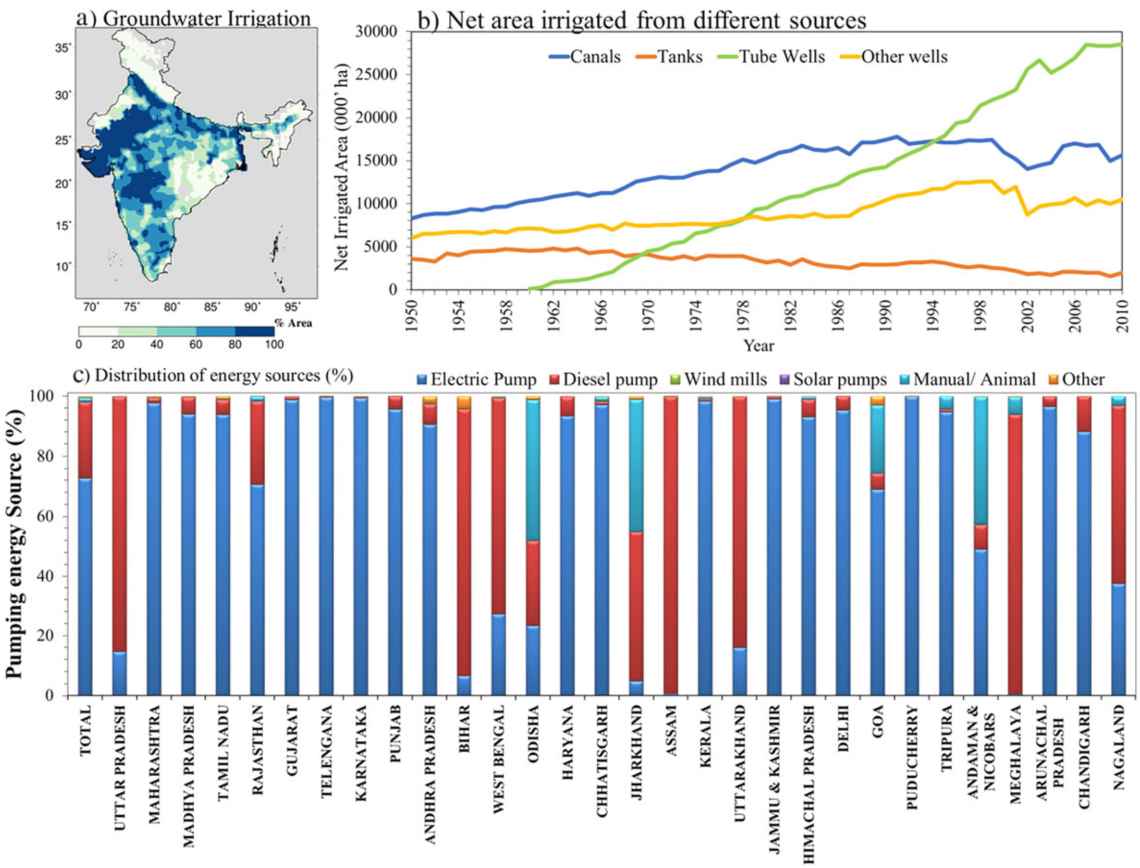

Figure 1. Groundwater pumping in India. (a) Area (%) irrigated with groundwater, (b) change in the net irrigated area from different sources, and (c) state-wise distribution of different energy sources used for groundwater pumping.

We use the data from the census of minor irrigation (http://micensus.gov.in/) to estimate the distribution of energy sources for groundwater withdrawal in India. We find that electric pumps cover about 70% of the total available pumping energy sources in India (Figure 1c). An exception is the Gangetic Plain, which is dominated by the presence of diesel pumps (Figure 1c). Electric pumps for groundwater irrigation are prominent in central, western, and southern India (Table S1 in the supporting information). India withdraws about 230-billion-m^3 groundwater to irrigate 45-million-ha gross cropped area (Shah et al., 2012).

We estimate the spatial distribution of groundwater depletion using well data from more than 24,000 wells located across India. Most of these are shallow wells (less than 30 m below ground level), and they do not account for groundwater pumping from deeper aquifers. After a rigorous quality check, we finally used 5,875 wells to estimate changes in groundwater storage in India (Figures 2 and S1). Over the last 21 years (1996–2016), a majority of districts experienced a decline in annual groundwater levels in India (Figure 2a). The districts with prominent decreases are located in the Indo-Gangetic Plain, northwest, and central (Maharashtra) regions (Figure 2a). A few districts located in Punjab experienced a substantial decline in groundwater table from 1996 to 2016. Groundwater depletion has been occurring at much faster rates (91 cm/year) in Punjab due to groundwater withdrawal from deeper wells (Singh et al., 2011). Districts with an increase in groundwater levels are scattered mostly in western India, east coast, and peninsular India (Figure 2a).

Overall, we find that a majority of districts in India experienced a substantial depletion in groundwater storage in the last 21 years (Figures 2 and S1d), and these findings are well supported with our observational and GRACE-based estimates (Figure 2). However, we find that the GRACE-based estimates show a rapid decline in groundwater storage (Figure 2c) in comparison to well estimates, which may be because most of the CGWB monitored wells are shallow and do not account for the pumping for irrigation in deep wells

10.1029/2018EF000939

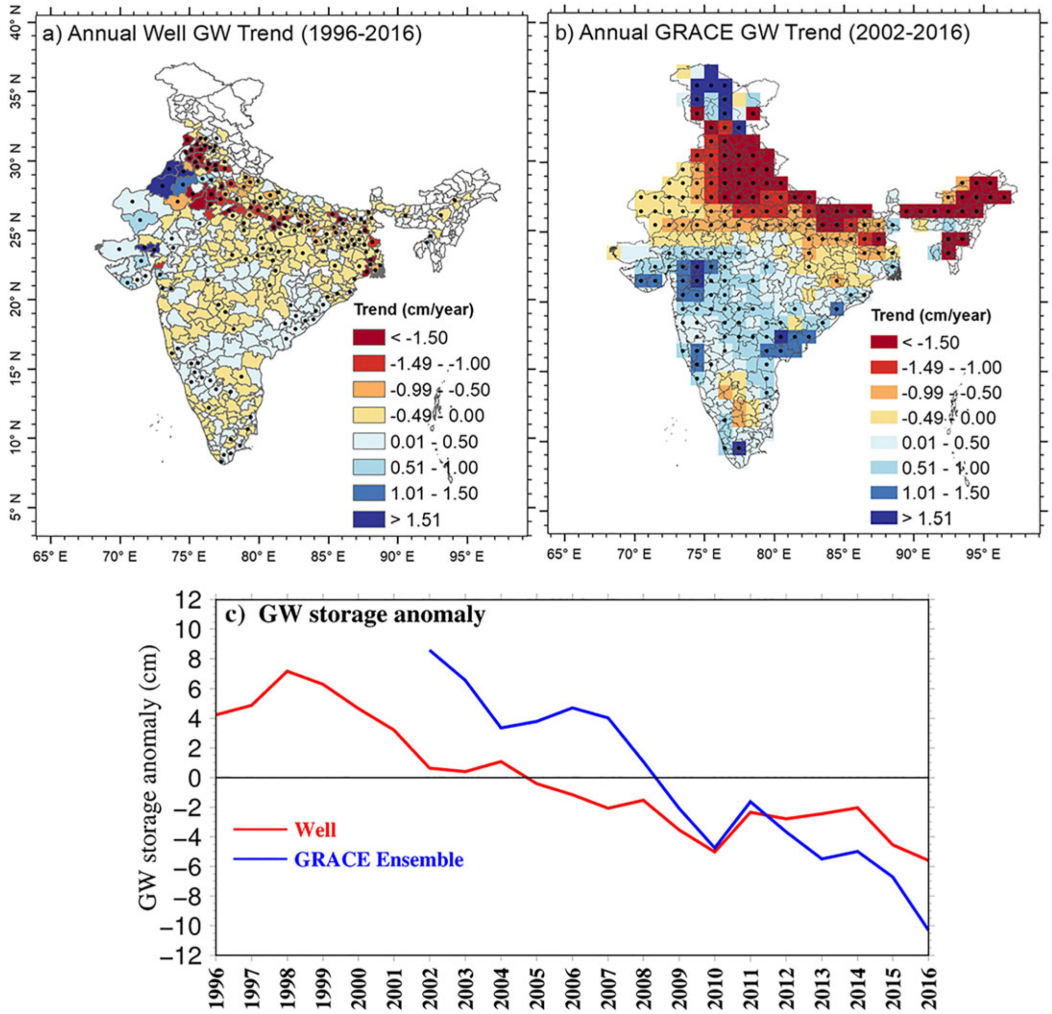

Figure 2. Groundwater (GW) depletion in India estimated using well and GRACE data sets. (a) mean annual trend in groundwater level (cm/year) during 1996–2016 estimated using well data from Central Ground Water Board, (b) trend in mean annual groundwater anomalies (cm/year) estimated using the GRACE satellite data for 2002–2016 period, (c) groundwater storage anomaly aggregated for all the districts that show groundwater depletion based on Central Ground Water Board well data and ensemble mean of GRACE products (Centre for Space Research, Jet Propulsion Laboratory, and Deutsches GeoForschungs Zentrum) for 2002–2016. Stippling in (a, b) shows statistically significant trend at 5% level. GRACE = Gravity Recovery Climate Experiment.

(Kaur & Vatta, 2015; Singh et al., 2011). We find that the regions with the substantial decline in groundwater storage (Indo-Gangetic Plain and northwestern India) have a high pump density (number of pumps/km^2) (Figure S2a) and groundwater withdrawal for irrigation (Figure S2b). In northwestern India, total groundwater withdrawal exceeds total annual groundwater recharge, leading to an overdraft of groundwater resources (Figure S2c). Overdraft of groundwater resources results in a large number of blocks falling in semicritical, critical, and overexploited category of groundwater resources (Figure S2d).

3.2. Estimates of CO_2 Release From Bicarbonates in Groundwater

Next, we estimate CO_2 emissions in India due to bicarbonate extraction using the well-distributed observations of groundwater and other characteristics (specific yield and bicarbonate (HCO_3^-) concentration). Major aquifers located in northern India and in the Indo-Gangetic Plain, which are alluvium, have higher specific yields (5–10%; Figure 3a). Other major aquifers located in central and lower part of western India placed in hard rock and basalts have low specific yields. Hard rock and basaltic aquifers are mainly located in peninsular India have more variability in recharge in response to rainfall in comparison to the aquifers located in

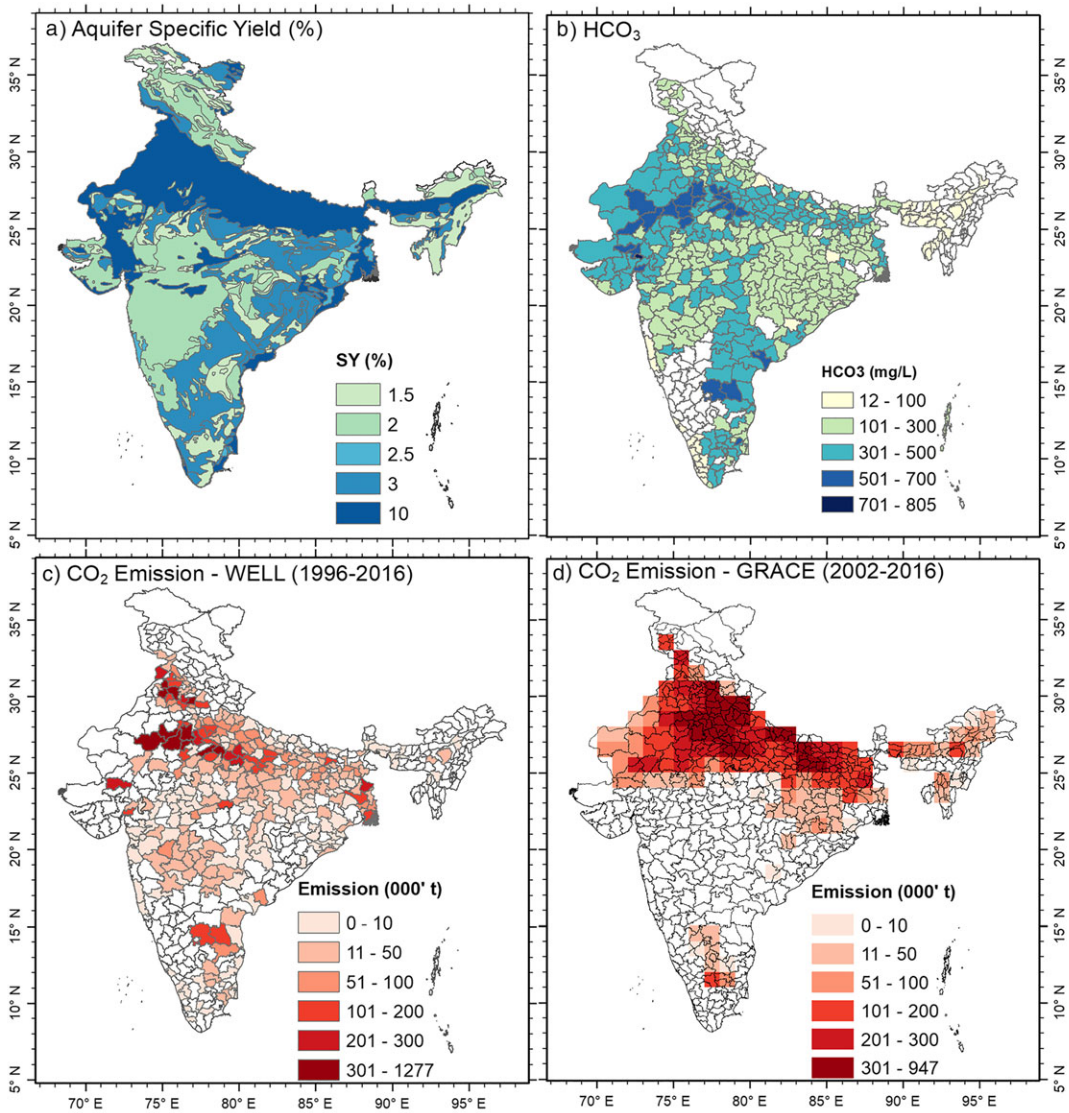

Figure 3. CO_2 emission in India due to groundwater depletion. (a) Specific yield (%) for major aquifers in India obtained from Central Ground Water Board, (b) district level mean bicarbonate (mg/L) concentration in groundwater, (c) CO_2 emission due to groundwater depletion (release of HCO3) during 1996–2016, and (d) CO_2 emission due to groundwater depletion based on the GRACE estimates during 2002–2016. Mean district level bicarbonate was estimated using the Central Ground Water Board monitoring wells in each district. GRACE = Gravity Recovery Climate Experiment.

northern India (Asoka et al., 2017). District level bicarbonate concentration is higher (more than 300 mg/L) in western India and part of the Indo-Gangetic Plain than that in other parts of India (Figure 3b). We find that in the Indo-Gangetic Plain and western India, bicarbonate concentration (~300 mg/L) is much higher than median bicarbonate (~190 mg/L) concentration reported for the United States (Wood & Hyndman, 2017).

We estimated CO_2 emissions due to bicarbonate extraction using the depleted volume of groundwater during 1996–2016 and equivalent CO_2 concentration (Figure 4c; see section 2 for more details). Most of the districts located in northern India and Indo-Gangetic Plain released higher CO_2 due to bicarbonate extraction than other regions (Figure 3c). Moreover, a few districts located in northwestern India witnessed a significant depletion of groundwater (Asoka et al., 2017; Rodell et al., 2009; Tiwari et al., 2009) also experienced a higher CO_2 emission (Figure 3c). Our estimates of CO_2 emissions using GRACE data are consistent with the well observations showing higher emissions from northwestern India and Indo-Gangetic Plain (Figure 3d). Total CO_2 emissions due to bicarbonate extraction (1996–2016) are 15.25 million tons (0.72 million tons/year).

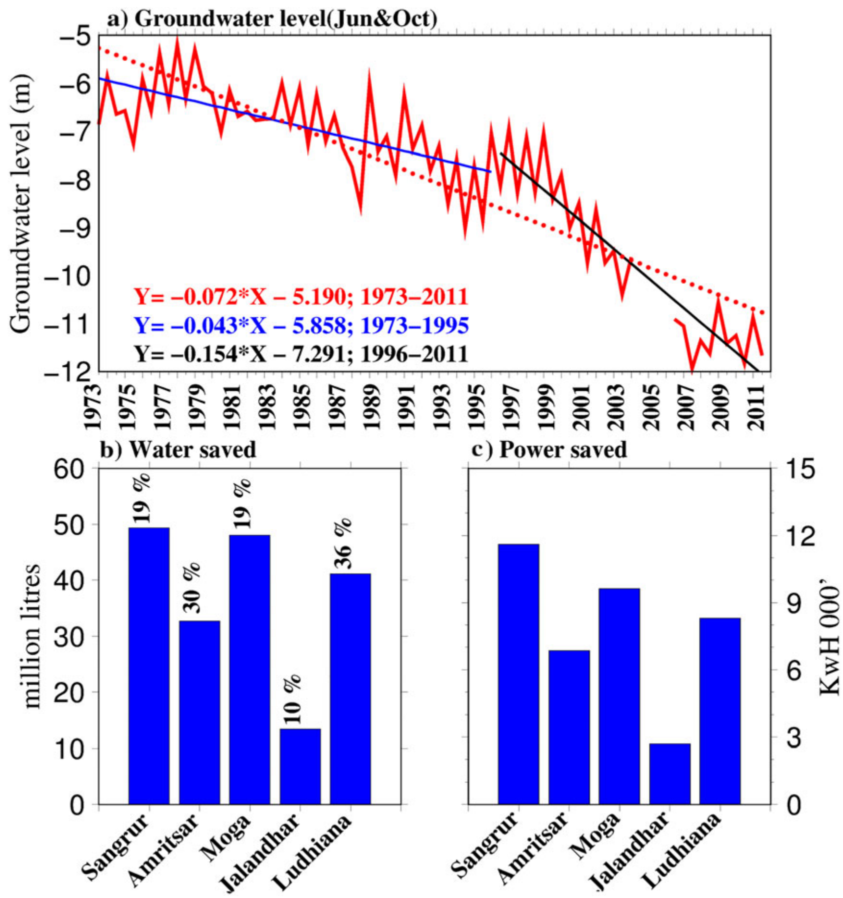

Figure 4. Technological intervention in the sustainable management of groundwater and energy consumption in Punjab. (a) Change in groundwater level in Punjab during 1973 and 2011 based on more than 1,750 wells, (b) savings in water (%) when irrigation decision was based on soil moisture information from tensiometers in five districts in Punjab, and (c) electricity saving (Kwh*1,000) in groundwater pumping in five districts in Punjab.

Our estimate of annual CO_2 emission rate of 0.72 million tons is lower than estimates of 1.7 million tons/year for the United States due to differences in HCO_3^- concentration (W. W. Wood & Hyndman, 2017).

3.3. Estimates of CO_2 Emissions due to Pumping Energy Requirements

Our estimates of CO_2 emissions for groundwater withdrawal are based on year 2015 for which CGWB provides state-wise groundwater withdrawal for irrigation (Table S2). We use the state-wise distribution of pumps (deep, shallow, and dug wells) from 2006–2007 census of minor irrigation (http://micensus.gov.in/; Table S3-S5). We assume that groundwater was pumped using electric pumps except for a few states (Uttar Pradesh, Bihar) where it is dominated by diesel pumps. We estimated CO_2 emissions due to groundwater pumping considering 30% and 40% pumping efficiency (Nelson et al., 2009; Patle et al., 2016; Shah, 2009; Wang et al., 2012). We used four (0.62, 0.95, 1.01, and 1.49 $kgCO_{2e}$/kWh) emission factors in our analysis (Karimi et al., 2012; Nelson et al., 2009; Patle et al., 2016; Shah, 2009; Tyson et al., 2012; Wang et al., 2012). Pumping of 1,000-m^3 groundwater per 1-m lift using an electric pump releases between 4.22 to 13.52 kg CO_2, considering 30% or 40% pump efficiency of electric pumps, and a emission factor between 0.62 to 1.49 $kgCO_{2e}$/kWh, assuming electricity from fossil fuel sources (Table S6). Central and western India is dominated by the presence of dug wells while shallow tube wells are predominately located in the Indo-Gangetic Plain and Karnataka. On the other hand, northwestern India is dominated by the presence of deep wells (more than 70-m depth; Tables S3–S5). We used the distribution of estimated pumping lift (Tables S3–S5) to determine CO_2 emissions for each state.

Total CO_2 emission was estimated for annual groundwater withdrawal of 222.38 billion m^3 for the year 2015 (Table S2). We distributed total annual pumped groundwater for each state in the proportion of deep, shallow, and dug wells. Therefore, our approach is different than previously reported (Nelson et al., 2009) by two ways: (1) consideration of distributed depth for groundwater pumping and (2) consideration of dug wells as they are in significant numbers in a few states. In a previous study, Nelson et al. (2009) used only shallow and deep wells with a fixed depth for CO_2 emissions. In our first approach, we estimate CO_2 emissions for each state using deep, shallow, and dug wells and actual pumping depth (Tables S3–S5) while the second approach is based on the fixed depth of 120, 35, and 40 m for deep, shallow, and dug wells, respectively. To pump 222.38 billion m^3 of groundwater, the total CO_2 emission is estimated to be between 31.29 and 100.26 million tons in 2015, considering distributed head (Table S6). Considering the constant depth of 120, 35, and 40 m for deep, shallow, and dug wells, respectively, the estimated total CO_2 emissions is between 40.89 and 131.02 million tons (Table S6).

Nelson et al. (2009) did not consider the dug wells in their analysis, which account for more than 46% of the total number of wells in India. The fraction of shallow and deep tube wells is 46% and 7.3%, respectively. Our estimate of annual CO_2 emissions (31.29–131.02 million tons) is a conservative estimate, as diesel pumps (mainly present in Uttar Pradesh and Bihar) cause less CO_2 emission than electric pumps. Our results show that the total annual CO_2 emissions due to groundwater depletion (bicarbonate extraction) and pumping in India is in the range of 32.01–131.74 million tons/year, which is less than 2–7% of the total CO_2 emissions from all the sectors, depending upon the combination of pump efficiency and emission factor (Garg et al., 2017).

3.4. Sustainable Management of Groundwater Resources and CO_2 Emissions

We use a unique data set collected at the farm level in Punjab to show a path of sustainable management of groundwater resources and CO_2 emissions (Figure 4). Groundwater well data collected from Punjab for more than 1,750 wells (including deep wells) show that the groundwater table has significantly (p value < 0.05) lowered after the green revolution in Punjab and more prominently during the recent decades (Figure 4a). This rate of groundwater depletion is much faster than our estimates based on the Central Groundwater Board's data for shallow wells. We experimented with sustainable use of groundwater resources in Punjab (Text S1). In five districts of Punjab, we provided tensiometers to about 500 farmers to monitor soil moisture condition in rice crops. We estimated water and energy saved in groundwater pumping for all the framers in the five districts. We find that irrigation based on tensiometer information to farmers results in 19%, 30%, 19%, 10%, and 36% of groundwater saving in comparison to the reference case irrigation without the information of soil moisture (Figure 4b). Additionally, this intervention also results in a significant reduction in the electricity consumption (Figure 4c). Our findings demonstrate that the decision making based on soil moisture conditions for irrigation has a potential and can be used as a sustainable measure to reduce groundwater pumping as well as CO_2 emission in Punjab. Therefore, for the sustainable management of rapidly depleting groundwater resources and CO_2 emissions, irrigation based on soil moisture information can play a significant role in India.

4. Discussion and Conclusions

While unsustainable depletion of groundwater due to pumping hampers food and freshwater security, it also results in CO_2 emission to the atmosphere. However, we find that combined CO_2 emissions because of bicarbonate extraction and pumping is less than 2–7% of total annual CO_2 emissions from India. Considering the size of irrigated agriculture and groundwater pumping in India, annual CO_2 emission related to groundwater-based irrigation is not a significant contributor to the total emissions (which may or may not have included these emissions accurately). Moreover, we report that bicarbonate extraction causes CO_2 emissions about 0.72 million tons/year, which is considerably lower than the estimates for the United States (Wood & Hyndman, 2017). Lower estimates of CO_2 emissions in India can be attributed to lower bicarbonate concentrations in comparison to the United States. Therefore, our results do not support the argument that groundwater depletion is a significant unreported source of CO_2 emissions as reported in Siebert et al. (2010). CO_2 emissions due to annual groundwater withdrawal of more than 222 billion m^3 (CGWB, 2014) is about

32.01–131.74 million tons, which is an insignificant fraction of the total CO_2 emissions of ~2 billion tons from India (http://www.moef.gov.in/sites/default/files/indbur1_0.pdf).

CO_2 emission due to groundwater pumping can be reduced by using solar and wind power instead of electricity- and diesel-based pumping systems and also by improving the pumping efficiency (Table S6). However, we notice that the regions (Indo-Gangetic Plain and northwestern India) with the higher groundwater abstraction and depletion have relatively low potential for the use of solar and wind power (Figure S3), indicating that these states require additional measures to reduce the dependence on electricity- and diesel-based groundwater pumping. Further, availability of solar and wind energy-based pumping will enhance groundwater depletion (Shah & Kishore, 2012), which is a major environmental degradation problem in the country. Reduction in subsidy in electricity prices can be a useful measure to reduce the pumping and encourage farmers for appropriate crop choices (Shah et al., 2012). Electricity cost of pumping groundwater for irrigation varies widely in India from $28 per hectares in Uttar Pradesh (lowest) to $560 per hectares (highest) in Karnataka; therefore, the abolition of subsidies may significantly reduce groundwater pumping and CO_2 emission (Shah et al., 2012).

For India, the environmental problem of groundwater depletion is much more serious than the associated CO_2 emissions, and hence, there is an urgent need for regulation of groundwater use. We demonstrate that technological intervention through agro-extension systems can result in sustainable management of depleting groundwater and CO_2 emissions in Punjab. Additionally, all forms of electricity subsidy, including that for the solar, need to be curbed, and an effective national groundwater monitoring and extraction program is needed. In the regions that are most affected by groundwater depletion (northwestern India and Indo-Gangetic Plain), a poor choice of crops and irrigation technology is the primary reason. For instance, despite the groundwater depletion in Punjab, the total area under rice has increased from 10% in 1975 to 38% in 2010 (Sarkar & Das, 2014), which resulted in a massive withdrawal of groundwater for irrigation leading to an overdraft condition (Figure S2). Average water requirement for water-intensive crops such as rice (1,200 mm) and sugarcane (2,000 mm) is far more significant than the other cereal crops (Reddy et al., 2015). The proper choice of crops, especially in northwestern India and Indo-Gangetic Plain can be a useful measure to reduce unsustainable extraction of groundwater. Along with appropriate crop choices, improving irrigation and water use efficiencies can reduce the amount of excessive extraction of groundwater by two third (R. Fishman et al., 2015). Therefore, technology- and policy-related decisions are required at multiple levels ensure sustainable management of groundwater resources in India.

Acknowledgments
The authors acknowledge funding from ITRA-Water project. The data used this study are publicly available from GRACE (https://grace.jpl.nasa.gov/) and CGWB (http://cgwb.gov.in/).

References

Aeschbach-Hertig, W., & Gleeson, T. (2012). Regional strategies for the accelerating global problem of groundwater depletion. *Nature Geoscience*, *5*(12), 853–861. https://doi.org/10.1038/ngeo1617

Asoka, A., Gleeson, T., Wada, Y., & Mishra, V. (2017). Relative contribution of monsoon precipitation and pumping to changes in groundwater storage in India. *Nature Geoscience*, *10*, 109–117. https://doi.org/10.1038/ngeo2869

Fishman, R., Devineni, N., & Raman, S. (2015). Can improved agricultural water use efficiency save India's groundwater? *Environmental Research Letters*, *10*(8), 084022. https://doi.org/10.1088/1748-9326/10/8/084022/meta

Fishman, R. M., Siegfried, T., Raj, P., Modi, V., & Lall, U. (2011). Over-extraction from shallow bedrock versus deep alluvial aquifers: Reliability versus sustainability considerations for India's groundwater irrigation. *Water Resources Research*, *47*, W00 L05. https://doi.org/10.1029/2011WR010617/full

Garg, A., Shukla, P. R., Kankal, B., & Mahapatra, D. (2017). CO2 emission in India: Trends and management at sectoral, sub-regional and plant levels. *Carbon Management*, *8*(2), 111–123.

Gleeson, T., VanderSteen, J., Sophocleous, M. A., Taniguchi, M., Alley, W. M., Allen, D. M., & Zhou, Y. (2010). Groundwater sustainability strategies. *Nature Geoscience*, *3*(6), 378.

Gleeson, T., Wada, Y., Bierkens, M. F. P., & van Beek, L. P. H. (2012). Water balance of global aquifers revealed by groundwater footprint. *Nature*, *488*(7410), 197–200. https://doi.org/10.1038/nature11295

Grubbs, F. E. (1969). Procedures for detecting outlying observations in samples. *Technometrics*, *11*(1), 1–21.

Hanasaki, N., Kanae, S., Oki, T., Masuda, K., Motoya, K., Shirakawa, N., Shen, Y., et al. (2008). An integrated model for the assessment of global water resources—Part 1: Model description and input meteorological forcing. *Hydrology and Earth System Sciences*, *12*(4), 1007–1025.

Karimi, P., Qureshi, A. S., Bahramloo, R., & Molden, D. (2012). Reducing carbon emissions through improved irrigation and groundwater management: A case study from Iran. *Agricultural Water Management*, *108*, 52–60.

Kaur, S., & Vatta, K. (2015). Groundwater depletion in Central Punjab: Pattern, access and adaptations. *Current Science*, *108*(4), 485–490.

Kulkarni, H., Shah, M., & Shankar, P. V. (2015). Shaping the contours of groundwater governance in India. *Journal of Hydrology: Regional Studies*, *4*, 172–192.

Mann, H. B. (1945). Nonparametric tests against trend. *Econometrica: Journal of the Econometric Society*, *13*(3), 245–259. Retrieved from http://www.jstor.org/stable/1907187

Nelson, G. C., Robertson, R., Msangi, S., Zhu, T., Liao, X., & Jawajar, P. (2009). Greenhouse gas mitigation: Issues for Indian agriculture. Intl Food Policy Res Inst.

Patle, G. T., Singh, D. K., Sarangi, A., & Khanna, M. (2016). Managing CO2 emission from groundwater pumping for irrigating major crops in trans Indo-Gangetic Plains of India. *Climatic Change*, *136*(2), 265–279. https://doi.org/10.1007/s10584-016-1624-2

Reddy, K. S., Kumar, M., Maruthi, V., Umesha, B., & Nageswar, C. V. K. (2015). Dynamics of well irrigation systems and CO2 emissions in different agroecosystems of South Central India. *Current Science*, *108*(11), 8.

Rodell, M., Velicogna, I., & Famiglietti, J. S. (2009). Satellite-based estimates of groundwater depletion in India. *Nature*, *460*(7258), 999–1002. Retrieved from http://www.nature.com/nature/journal/v460/n7258/abs/nature08238.html

Sarkar, A., & Das, A. (2014). Groundwater irrigation-electricity-crop diversification nexus in Punjab, (52), 10.

Sen, P. K. (1968). Estimates of the regression coefficient based on Kendall's tau. *Journal of the American Statistical Association*, *63*(324), 1379–1389. https://doi.org/10.1080/01621459.1968.10480934

Shah, T. (2009). Climate change and groundwater: India's opportunities for mitigation and adaptation. *Environmental Research Letters*, *4*(3), 035005. https://doi.org/10.1088/1748-9326/4/3/035005

Shah, T., Giordano, M., & Mukherji, A. (2012). Political economy of the energy-groundwater nexus in India: Exploring issues and assessing policy options. *Hydrogeology Journal*, *20*(5), 995–1006. https://doi.org/10.1007/s10040-011-0816-0

Shah, T., & Kishore, A. (2012). Solar-powered pump irrigation and India's groundwater economy: A preliminary discussion of opportunities and threats.

Shankar, P. V., Kulkarni, H., & Krishnan, S. (2011). India's groundwater challenge and the way forward. *Economic and Political Weekly*, 37–45.

Siebert, S., Burke, J., Faures, J.-M., Frenken, K., Hoogeveen, J., Döll, P., & Portmann, F. T. (2010). Groundwater use for irrigation—A global inventory. *Hydrology and Earth System Sciences*, *14*(10), 1863–1880. Retrieved from http://www.hydrol-earth-syst-sci.net/14/1863/2010/

Singh, A., Phadke, V. S., & Patwardhan, A. (2011). Impact of drought and flood on Indian food grain production. In S. D. Attri, L. S. Rathore, M. V. K. Sivakumar, & S. K. Dash (Eds.), *Challenges and opportunities in agrometeorology*, (pp. 421–433). Berlin Heidelberg: Springer. https://doi.org/10.1007/978-3-642-19360-6_32

Tiwari, V. M., Wahr, J., & Swenson, S. (2009). Dwindling groundwater resources in northern India, from satellite gravity observations. *Geophysical Research Letters*, *36*, L18401. https://doi.org/10.1029/2009GL039401

Tyson, A., George, B., Aye, L., Nawarathna, B., & Malano, H. (2012). Energy and greenhouse gas emission accounting framework for groundwater use in agriculture. *Irrigation and Drainage*, *61*(4), 542–554.

Wada, Y., van Beek, L. P. H., van Kempen, C. M., Reckman, J. W. T. M., Vasak, S., & Bierkens, M. F. P. (2010). Global depletion of groundwater resources: Global groundwater depletion. *Geophysical Research Letters*, *37*, L20402. https://doi.org/10.1029/2010GL044571

Wang, J., Rothausen, S. G. S. A., Conway, D., Zhang, L., Xiong, W., Holman, I. P., & Li, Y. (2012). China's water-energy nexus: Greenhouse-gas emissions from groundwater use for agriculture. *Environmental Research Letters*, *7*(1), 014035. https://doi.org/10.1088/1748-9326/7/1/014035

Wood, W. W., & Hyndman, D. W. (2017). Groundwater depletion: A significant unreported source of atmospheric carbon dioxide. *Earth's Future*, *5*(11), 1133–1135.